Muon Storage Rings as a Novel Neutrino Source

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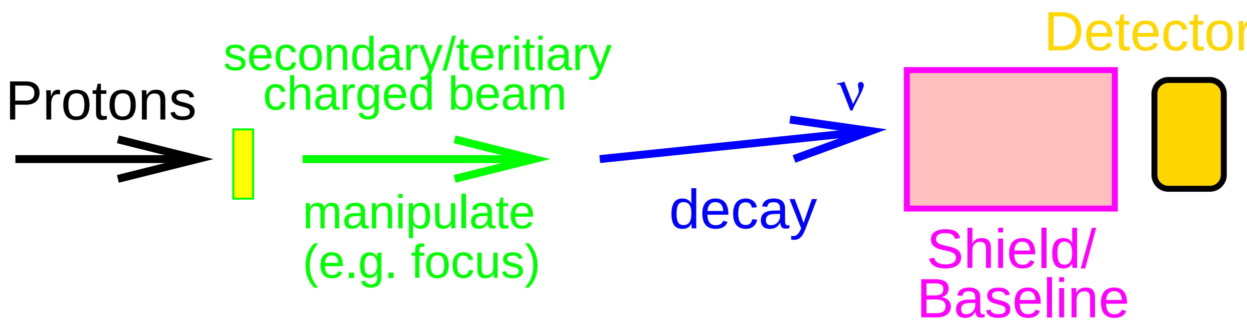
Outline

1. Why Muons as a Source?
2. Anatomy of a "Neutrino Factory"
3. Capabilities:
   - Long-baseline neutrino oscillations
   - High rate neutrino experiments
4. Conclusions

Why Muon Decays?



"Conventional" ν beams are produced by

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\tau_{\pi^\pm} \sim 25 \text{ ns}$$

Muon decays

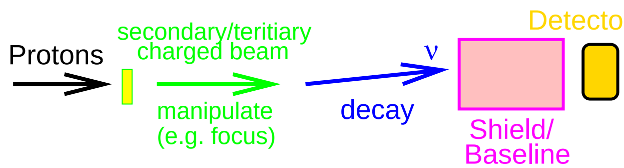
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$$

$$\tau_\mu \sim 2\ \mu\text{s}$$

$\pi^+ \rightarrow \mu^+ \nu_\mu$	$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$
Can focus, but large emittance	Time to cool and focus
$Q \sim 34$ MeV	$Q \sim 105$ MeV
ν_μ, $\overline{\nu_\mu}$ only	ν_μ, $\overline{\nu_\mu}$, ν_e, $\overline{\nu_e}$

Neutrino Detection Rates

Neutrino event rates depend on a relatively small number of factors



- Parent decays
- Neutrino beam divergence
  ("spot size" at the detector)
  From parent decay kinematics,

$$N_\nu \overset{\propto}{\sim} \frac{1}{\langle\theta_\nu\rangle^2}, \quad \langle\theta_\nu\rangle = \frac{\pi}{4\gamma_{\text{parent}}}$$

- Neutrino energy

$$\sigma(\nu N \to \ell^\pm X) \propto G_F s$$

- "Baseline", i.e. distance to detector
  (may be determined by physics goals)

$$N_\nu \propto \frac{1}{L^2}, \quad L \text{ large}$$

Muons as a source potentially win in decays, divergence and energy due to long lifetime!

Beam Divergence

Key difference between conventional and muon source is optimization of tradeoff of parent production rates and beam divergence

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Conventional ($\pi^{\pm}$) Beam Economics

- Production rates fall steeply with increasing E_{π} (production cross-section, proton acceleration)
- $N_{\nu} \overset{\propto}{\sim} N_{\pi} {E_{\pi}}^{3}$ (neutrino cross-section, divergence)

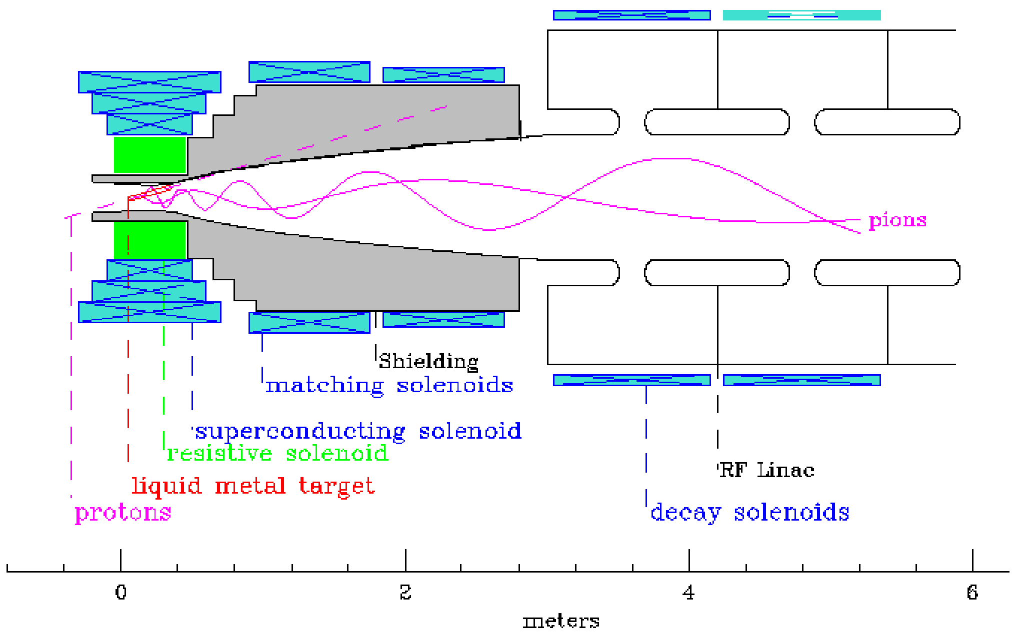
μ Beam Economics

- Produce and capture at low energies (large cross-section, higher p power)
- Accelerate parent beam after cooling $N_{\nu} \overset{\propto}{\sim} (N_{\mu} {E_{\mu}}^{3})$

Benefits are great...

...so can it be done?

A Resounding "Maybe"



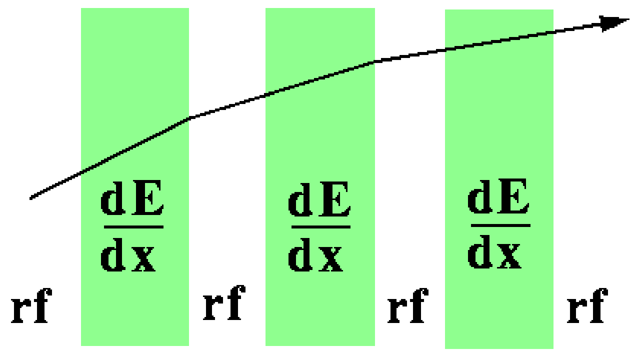
Requirements

- **Very intense proton source**
  $\mathcal{O}(10^{14})$ protons, 15 Hz, 1 ns bunches
  (S.D.Holmes *et al.*, FERMILAB-TM-2021)
- Pion Capture
  - ▷ Collection efficiency: 0.6 π^+ per proton
  - ▷ $p_z \sim p_t \sim 200$ MeV
  - ▷ $\sigma(\Delta E/E) \approx 1$
  - ▷ ...and then it decays to muons
- Left with a very large muon beam

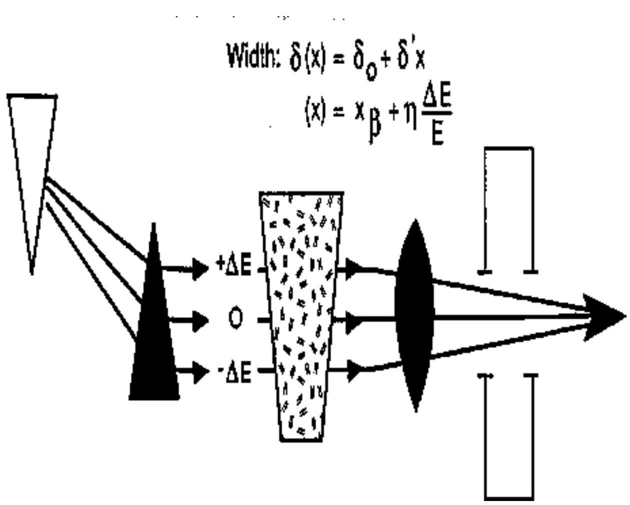
A Resounding "Maybe" (cont'd)

Hot muon beam $\longrightarrow$ storable muon beam

- Cool *via* multiple scattering alternating with longitudinal acceleration
  "Ionization Cooling" (Skirnsky and Parkhomchuk, 1981)



- Strong focusing needed



- Transverse emittance $\longrightarrow$ longitudinal emittance

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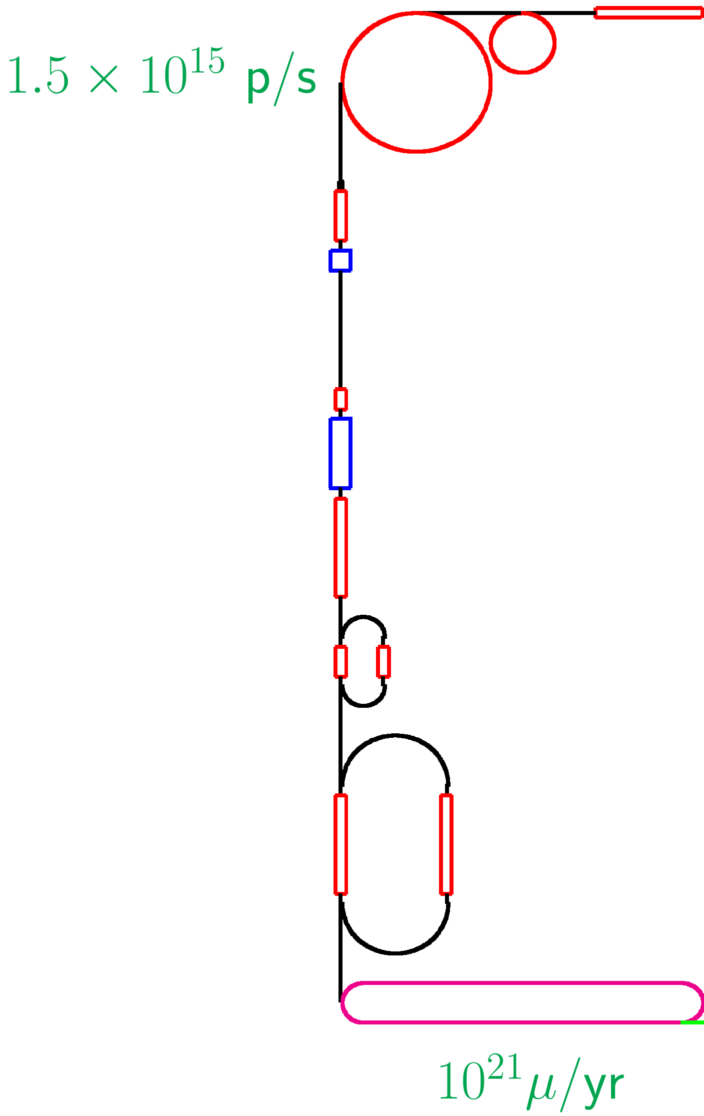
MUCOOL R& D program:

http://www.fnal.gov/projects/muon_collider/cool.html

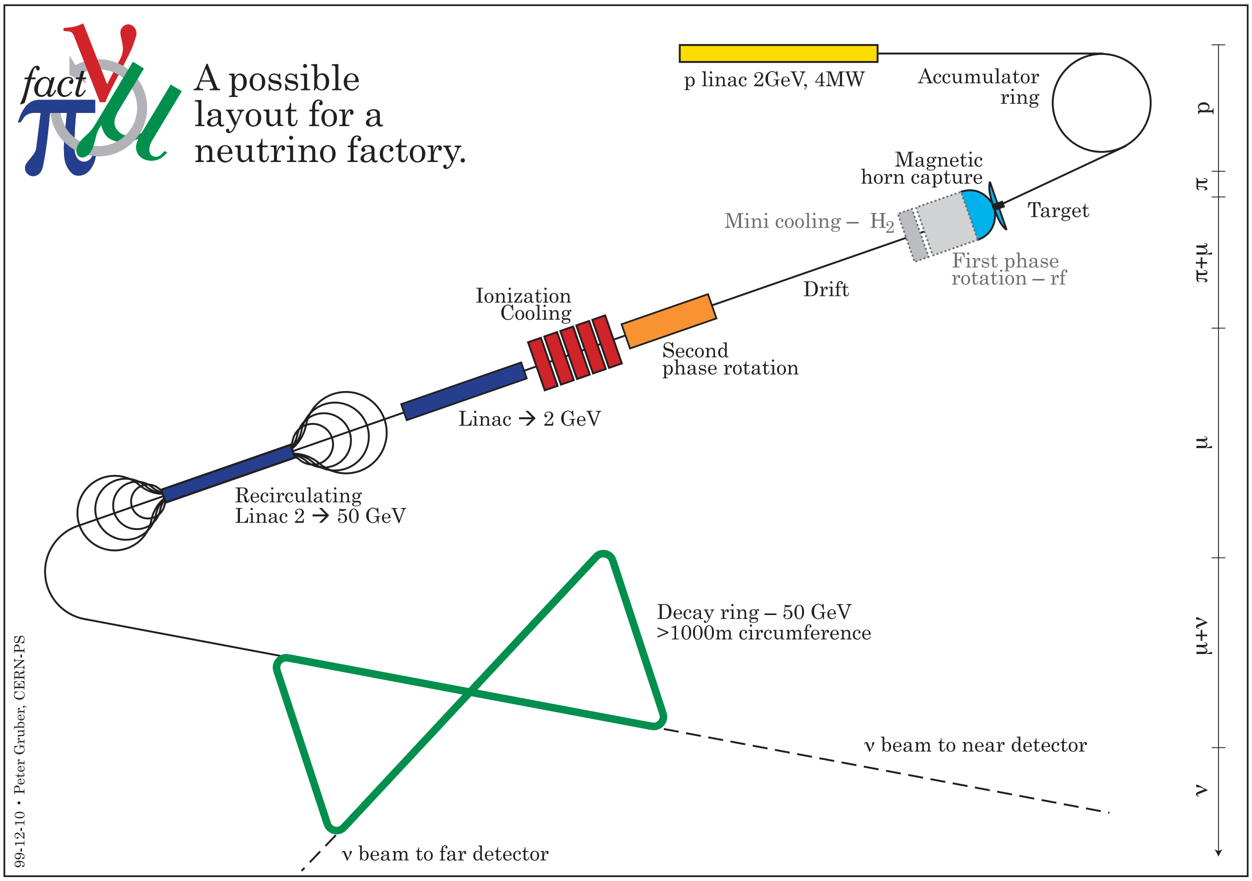
A "generic" neutrino factory design



		μ/p
Proton Driver		
Target		0.44
Phase Rotate #1	**(42 m rf)**	0.2
Mini Cooling	**(3.5 m H_2)**	
Drift	**(160 m)**	
Phase Rotate #2	**(10 m rf)**	0.14
Cooling	**(80 m)**	0.09
Linac	**(2 GeV)**	
Recirc. Linac #1	**(2-8 GeV)**	
Recirc. Linac #2	**(8-50 GeV)**	0.06
Storage Ring	**(50GeV 900m circ)**	

Neutrino Beam

"Neutrino Factory" Design (cont'd)



- NSF initiative through Neutrino Factory and Muon Collider Collaboration

  `http://www.cap.bnl.gov/mumu/mu_home_page.html`

- Active Accelerator, Detector and Physics working groups at FNAL and CERN

  `http://www.fnal.gov/projects/muon_collider/`

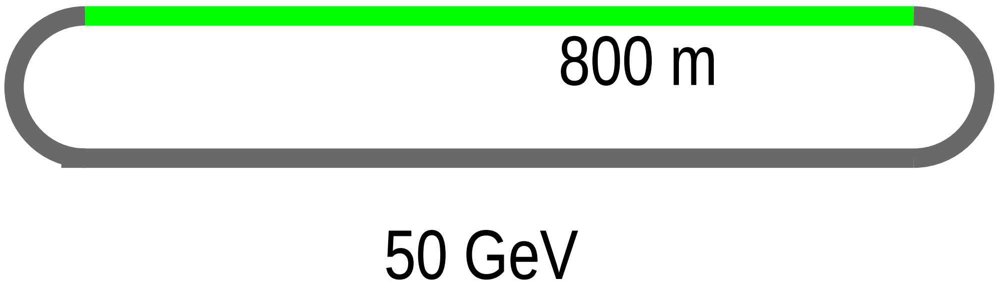
  `http://muonstoragerings.cern.ch/Welcome.html/`

- All contributions to working groups welcomed!

Expected Neutrino Rates

Assumed Parameters (FNAL study group)

- 10^{20}/yr μ decays in the green straight section $\Rightarrow$



c.f.: Competing facilities

Beam	$\langle E_\nu \rangle$ [GeV]	ν per year
NuTeV/CCFR (Fermilab)	100	$\sim 10^{14}/\mathrm{m}^2$
CHORUS/NOMAD (CERN)	30	$\sim 3 \times 10^{15}/\mathrm{m}^2$
MINOS Near (Fermilab)	15	$\sim 10^{17}/\mathrm{m}^2$
Neutrino Factory	30	$5 \sim 10^{19}/\mathrm{m}^2$

Highly intense beams can...

- Contend with $1/L^2$
  - ▷ Long-baseline neutrino oscillations
- Or defeat small G_Fs.
  - ▷ High rate neutrino experiments

Goals of Neutrino Oscillation Studies at a Neutrino Factory

In 10 years time...

- LSND will be confirmed/refuted. If confirmed, could know $\delta m12^2$ to 0.1eV^2, and $\sin^2 2\theta_{12}$ to 10%
- K2K & MINOS will confirm/refute atmospheric neutrino anomaly $(\nu_\mu \to \nu_\tau)$
- SuperK & MINOS may rule out $\nu_\mu \to \nu_{\mathrm{sterile}}$ (Estimate δm^2_{23} known to 30%, $\sin^2 2\theta_{23}$ to 20%)
- SNO & Borexino will determine if solar $\nu_e \to \nu_{\mathrm{sterile}}$ Perhaps (with SuperK, KAMLAND) can determine correct solar solution

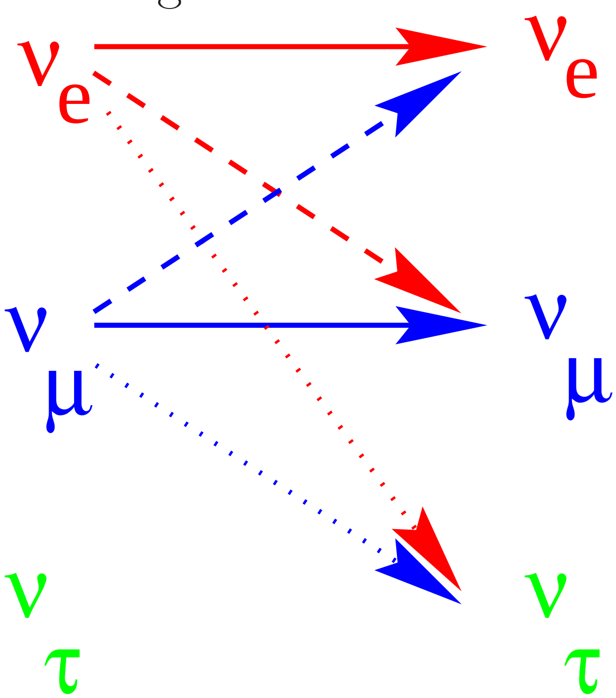
Most likely scenario: there will be 3 or more confirmed generations contributing to oscillations.

Remaining Questions to answer:

- Is 3-generation mixing matrix unitary?
- How is the mass hierarchy arranged?
- Is there CP violation?
- Observation of matter effects in accelerator beam?
- If sterile neutrinos: how many?

Muon Storage Ring Capabilities

Looking for these flavor transitions

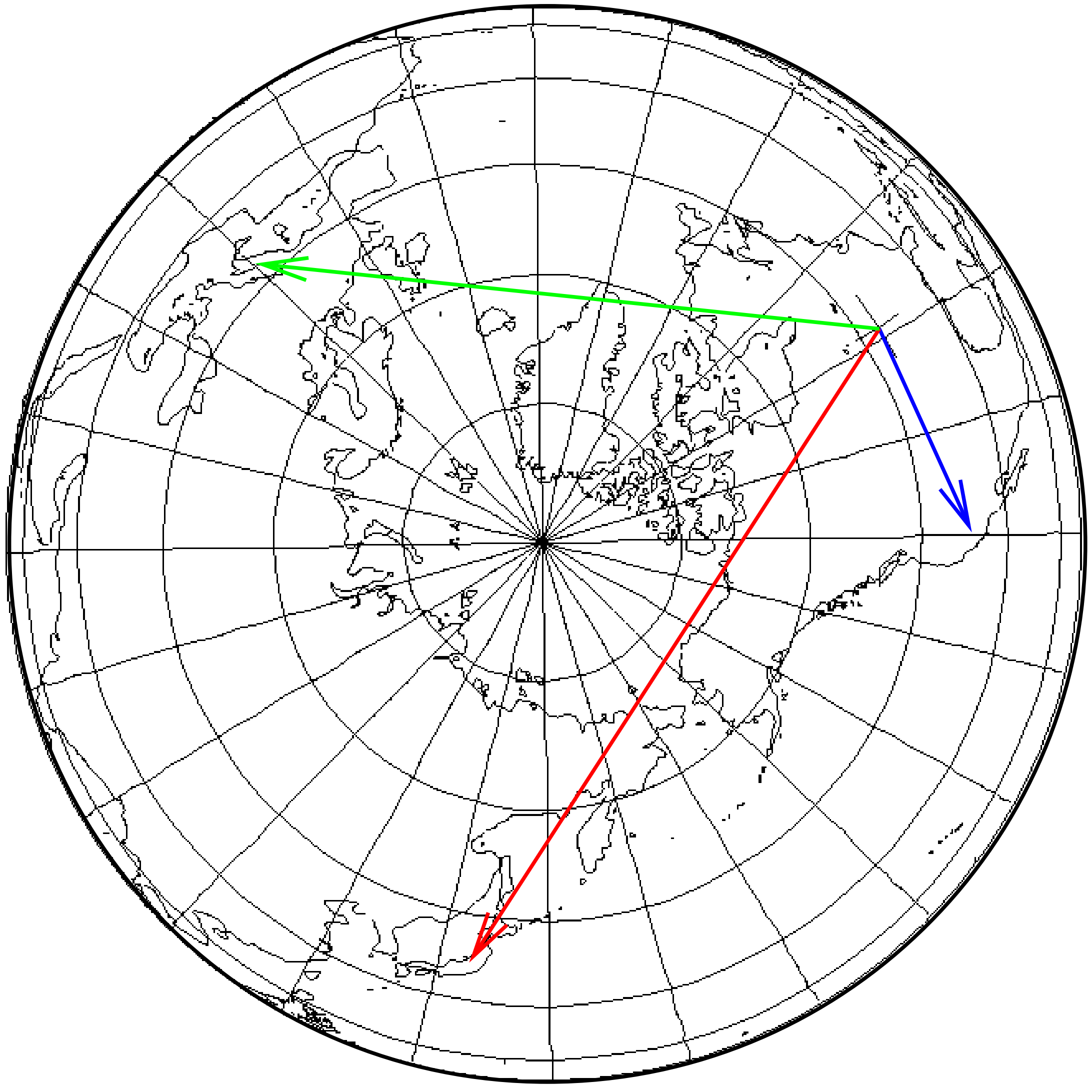


And their CP conjugates...

And looking for transitions from competing processes

- Three-generation oscillations
- Oscillations and matter transitions

Ideas for Neutrino Oscillation Experiments



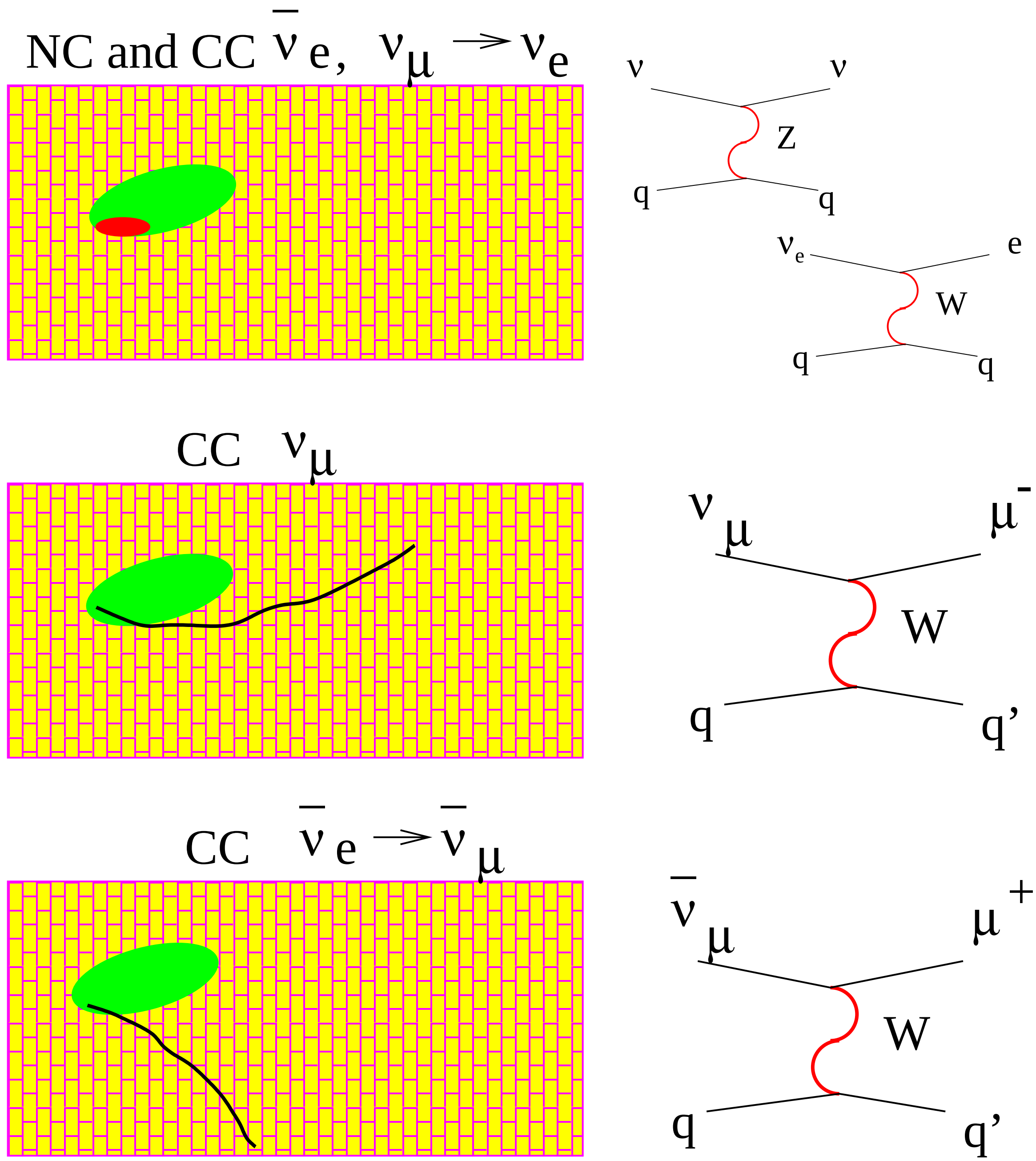
30 GeV Neutrino Beams

Baselines of few or many thousand kilometers

International Collaboration

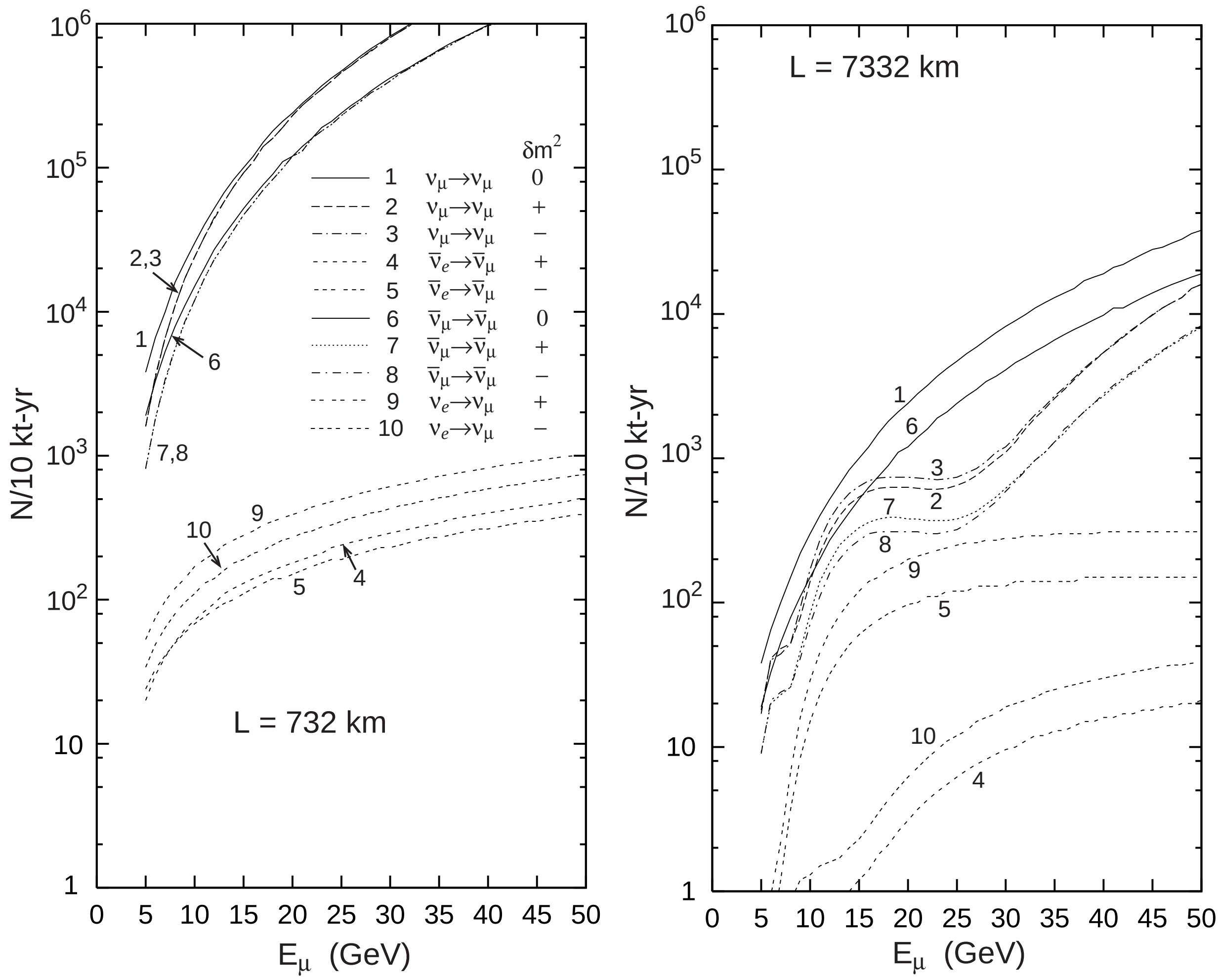
Most Simple Experiment: Wrong Sign Muons

Large (kTon) magnetized sampling/tracking calorimeter



Wrong-sign muon appearance is distinctive signature

Fermilab → Soudan or Gran Sasso?



$$sin^2 2\theta_{13} = 0.04,\ |\delta m^2_{21}| = 5 \times 10^{-5} eV^2$$
$$|\delta m^2_{32}| = 3.5 \times 10^{-3} eV^2$$

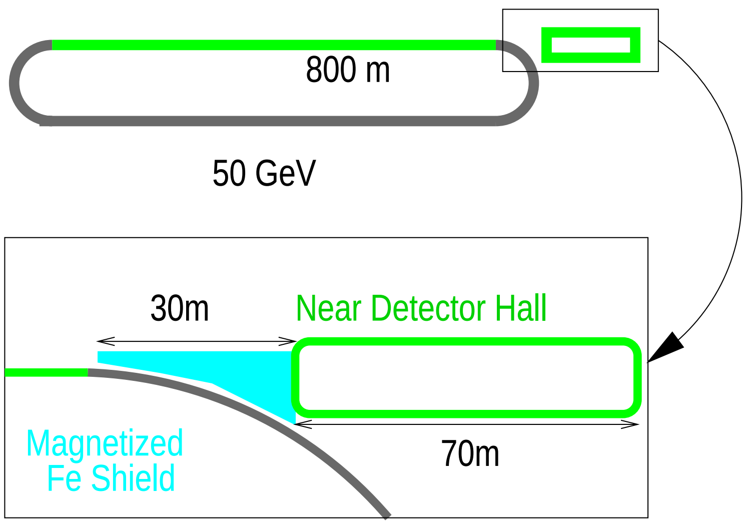
(V. Barger, S. Geer, R. Raja, K. Whisnant, `hep-ex/9911524`)

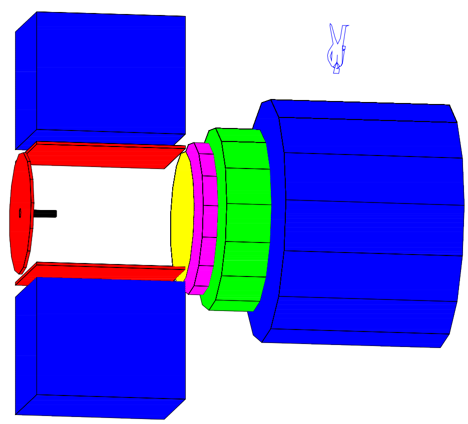
- May want multiple baselines simultaneously
- Messy details like backgrounds are key in optimizing experiment. . .

High Rate Neutrino Experiments

10^{20}/yr μ decays in the green straight section $\Rightarrow$

- 5–8% of all interactions within $r < 10$ cm
- 40–50% of all interactions within $r < 50$ cm
- $1.5\text{–}3 \times 10^6 \times \frac{E_\mu}{50\ \mathrm{GeV}}$/kg/yr at beam center





(multi-purpose detector design of B. King)

Small targets open up new possibilities in

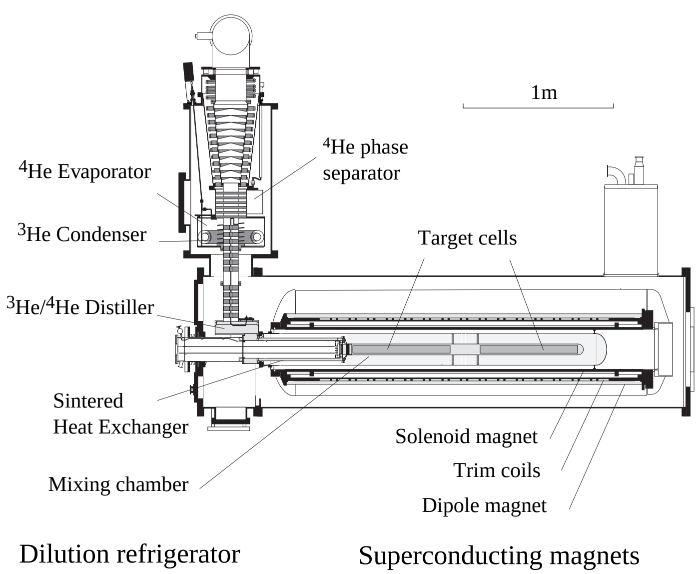
- **Target material**
- Final state detection

$\Longrightarrow$ New physics opportunities

Nucleon Structure at a Neutrino Factory

Why use neutrinos to probe nucleon structure?

- xF_3: separate sea and valence
- Flavor tagging
  - ▷ $\nu s \to \mu^- c$, $c \to X\ell\nu$ tags strange quarks
  - ▷ $\nu d \to \mu^- u$ but $\overline{\nu} u \to d\mu^+$
  - ▷ $\nu c \to \nu^- c$, $c \to X\ell\nu$ (? hard...)
- High rate means we can wean νN from its addiction to heavy isoscalar targets
  - ▷ Polarized Targets?



  - ▷ Solid Butanol, dilution factor of 0.1 (SMC)

Example: Polarized Target Experiment

(D. Harris, KSM)

Goal: Flavor-Separated Spin

$$\nu u \to \ell^- d \qquad \nu \overline{d} \to \ell^- \overline{u}$$
$$\overline{\nu} d \to \ell^+ u \qquad \overline{\nu} \overline{u} \to \ell^+ \overline{d}$$
$$\overline{\nu} s \to \ell^+ c \qquad \nu \overline{s} \to \ell^- \overline{c}$$

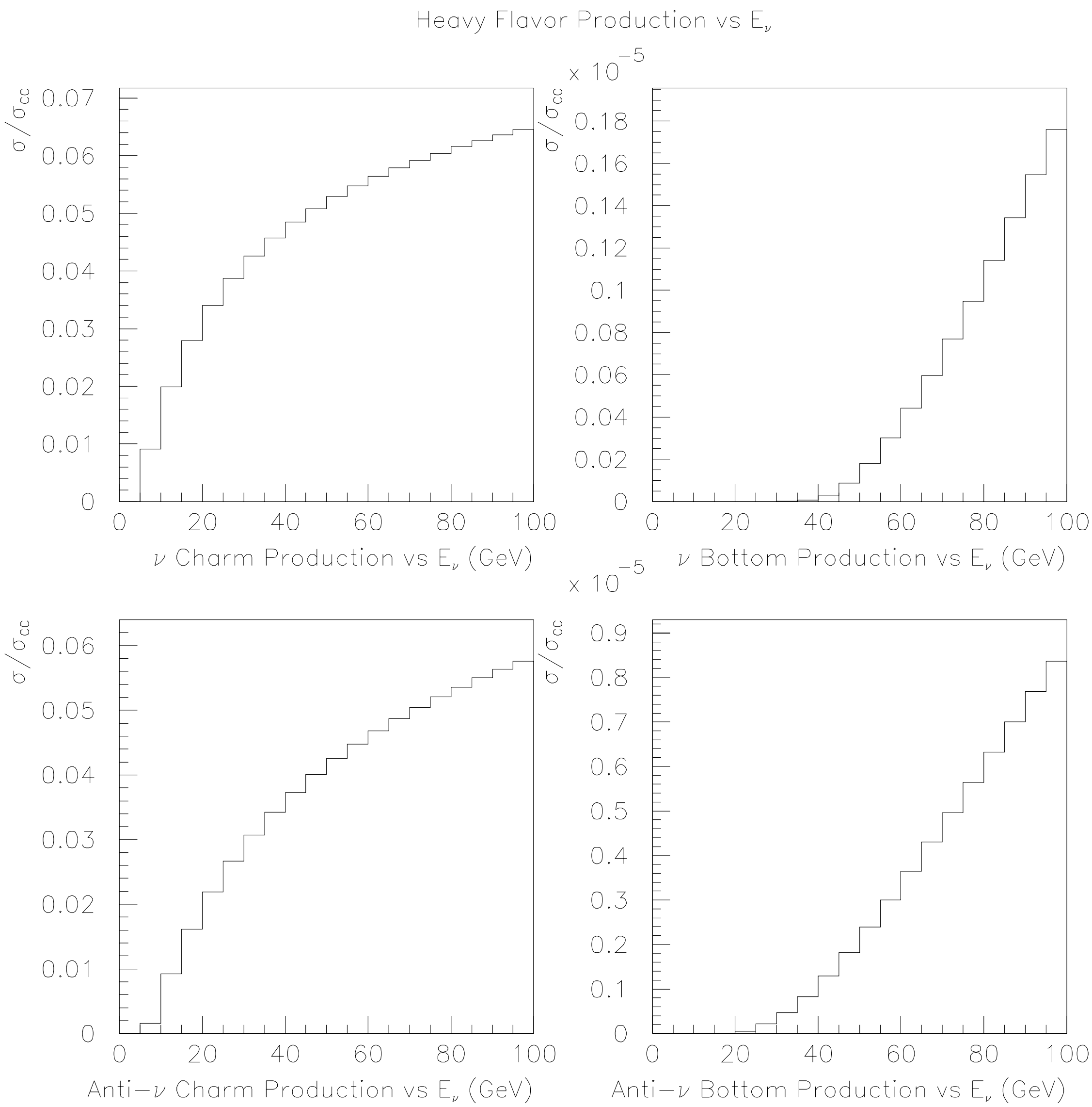
- q and $\overline{q}$ from the inelasticity distributions
- $\nu/\overline{\nu}$ from lepton flavor

$\overline{\nu}(\nu)s(\overline{s}) \to \mu^{\pm}c(\overline{c})$ separated from $c \to \ell\nu X$ final states ($\sim 1\%$ of cross-section at 50 GeV)

$\Rightarrow$ Measure strange sea polarization to $\sim 1\%$ precision (one year)

- Vastly superior flavor separation compared to hadron-based separation in HERMES

Neutrino Charm Factory: By-Products



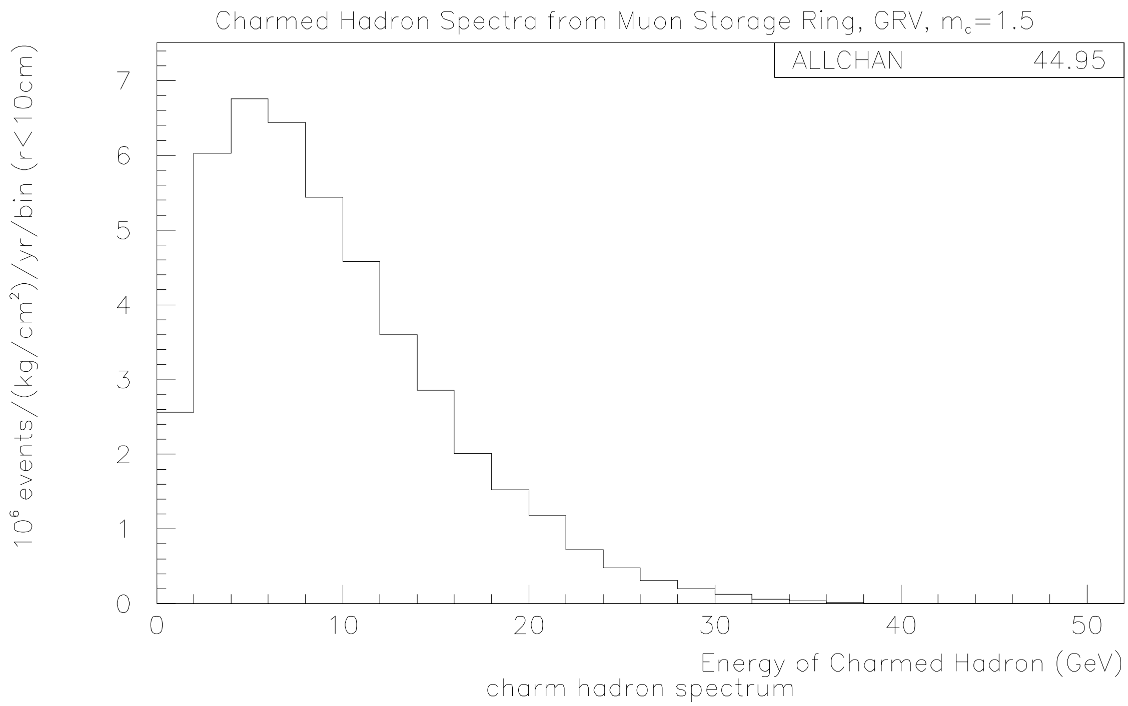
$$\frac{\sigma_{\text{charm}}}{\sigma_{\text{CC}}} \qquad\qquad \frac{\sigma_{\text{bottom}}}{\sigma_{\text{CC}}}$$

- Charm Production averages $\approx 3\%$ of cross-section
- Bottom Production not accessible at 50 GeV

  ▷ precise measure of $|V_{ub}|$ at high E_ν? (B. King)

Neutrino Charm Factory II

- Charm spectrum is soft by fixed target standards
- Still, 10^5/kg-yr charmed hadrons above 10 GeV



- Rate is high; non-charm backgrounds relatively low
- Tagging
  - ▷ $\nu\, s \rightarrow \ell^- c$
  - ▷ $\overline{\nu}\, \overline{s} \rightarrow \ell^+ \overline{c}$
  - ▷ Tagging backgrounds are typically very low
    - $*$ Most common mistag from $c \rightarrow \ell^+ X \nu$ (benign since charm is misreconstructed also)
- So what to do with $\sim 10^8$ tagged charm?

$D^0 - \overline{D}^0$ Mixing

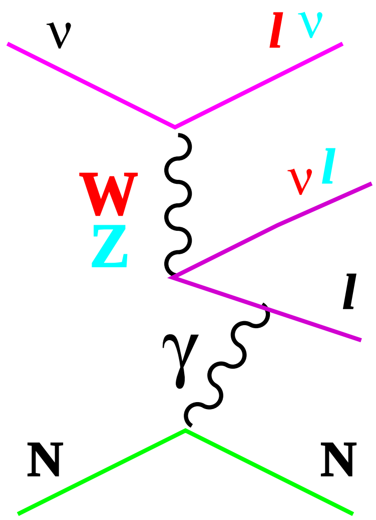
- $D^0 - \overline{D}^0$ is a clean signature of new physics if seen above 10^{-6} level
- e^+e^- and Fixed Target currently at few$\times 10^{-3}$ level (BaBar estimates few10^{-4} sensitivity with years at design luminosity)
  - ▷ Stuck on systematics/backgrounds
  - ▷ Reconstructed flavor from $D^0 \to K^-\pi^+$ (but $D^0 \to K^+\pi^-$ is 1% of this rate)
  - ▷ Proper lifetime analysis required to get below 10^{-2}

One idea for $D^0 - \overline{D}^0$ Mixing in a Neutrino Factory Beam:

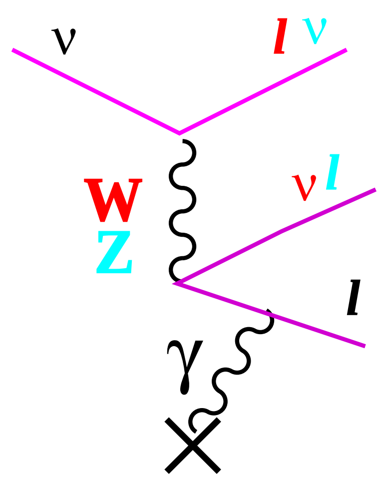
- High momentum lepton is tag
- Measure (inclusive) second lepton charge
  - ▷ about 30% from neutral D mesons
  - ▷ 10% efficient, assuming only $e^\pm$ useful
    - ∗ There is a few$\times 10^{-2}$ background from light meson decays in showers for the case of muons
  - ▷ probe 5×10^6 D^0 decays
- $D^0 - \overline{D}^0$ mixing gives $\ell^\pm_{\mathrm{tag}}\ell_{\mathrm{charm}^\pm}$
  - ▷ vs dominant $\ell^\pm_{\mathrm{tag}}\ell^\mp_{\mathrm{charm}}$

"External Tridents"

(A. Melissinos, KSM)



Nuclear form-factor leads to a large uncertainty in the cross-section



External field!
(well-determined, but weaker)

$$\sigma_{\nu\gamma} = \frac{\alpha G_F^2 s}{9\pi^2} \log \frac{s}{s_{\min}}$$

"External Tridents" (cont'd)

(A. Melissinos, KSM)

In an external magnetic field:

$$P_{\ell^+\ell^-} = \frac{\alpha G_F^2 s}{9\pi^2} \log \frac{s}{(2m_e)^2} \frac{B^2 E_\nu}{2m_\ell^2} l$$

For a 2 T, 10 m long field 20 cm in radius (50 GeV μ beam),

$$N_{e^+e^-} \sim 3 \times 10^3/\text{yr}$$
$$N_{\mu^+\mu^-} \sim 0.03/\text{yr}$$

- Signal is low mass, forward e^+e^- pairs from external field and nothing else
- High rate
- Needs a ν_e or $\overline{\nu}_e$ beam to test interference of W/Z terms (T. Bolton)
- Sensitive to anomolous $W\gamma$ or $Z\gamma$ couplings(?)

Direct Probes of Neutrino Properties

Some of the laundry list:

- Charge radius $< r^2 >$ as an elastic form-factor or radiative emission
- Decays of heavy neutrinos with $m_{L^0} \sim 50$ MeV
  $m_{L^0} \to e^+e^-\nu$
- Interaction/modification of ν beam in high external field
- ...

Why persue these at a muon storage ring neutrino source?

- Roughly 10^4 increase in available neutrino fluxes

Conclusions

1. Exciting Times!
   Accelerator R&D efforts are suggesting the possibility of high intensity, accelerated beams of muons
   - Collimated, high rate ν_μ and ν_e beams
2. Long Baseline Oscillation Capabilities
   - Probe CP violation, matter effects, unitarity of mixing matrix
3. Many high rate experiments supported by such a facility as well
   - Interesting and diverse physics menu
   - Surprises here?
   - May attract a large experimental community